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Assessment of engineering geology and grouting applications in Yalnızardıç Dam Site (Antalya, Türkiye)

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Abstract
The Yalnızardıç roller compacted concrete (RCC) dam, constructed in 2015, is located in the Mediterranean region of Turkey, intended for electric power production. It is approximately 303 m long and 92 m in height. In this paper, it is aimed to determine the performance of the grouting method, conducted to control the water seepage and improve the foundation of the Yalnızardıç dam. The engineering properties of the site were introduced by geological mapping, drilling, and laboratory tests. The seepage of the foundation was determined by the in-situ Lugeon test method, also referred to as a water pressure test, which is estimate the mean hydraulic conductivity of rock mass. As a result of the tests, high-permeable and permeable zones were determined in the dam axis area. To make a barrier layer for these permeable zones, grout curtains were built in the left abutment, thalweg and right abutment with two lines of grouting holes which is proposed according to the Lugeon test and rock quality designation (RQD) results. Consolidation grouts were built to increase the density of the soil which makes the strength of the dam's foundation. After the groutings, check boreholes were drilled and water pressure tests were performed to control the seepage along the foundation and dam site. The results indicated that average Lugeon (LU) values reduced, and the values were within the recommended limit. The process shows considerable accuracy in evaluating grouting efficiency.

1. Introduction

Yalnızardıç Dam Hydroelectric Power Plant is located in the Mediterranean region within the borders of Antalya on the northeastern part of Alanya, Turkey (Figure 1). It is built to produce energy by utilizing the available water potential of the Gevne Stream that flows through the Göksu Basin. The research region is situated between the heights of 1385 m and 1205 m in the Göksu River Basin on the Gevne Stream, which is the source branch of the Ermenek Stream of this river. The installed capacity amounts to 33.13 MW, with an energy production of 90 GWh per year. The average annual discharge is 8.76 m3/s, and the average yearly water volume totals 276.10 hm^3. The maximum water level of the dam lake reaches 1359.40 m, with a total storage volume of 109.525 hm^3. A circular diversion tunnel with a diameter of 4 m and length of 230 m was constructed. A summary of the dam's characteristics includes a crest elevation of 1361 m, a crest length of 303 m, and a crest width of 12 m. The thalweg elevation is 1269 m, with a foundation elevation of 1263 m. The dam's height from thalweg is 92 m, and its body fills volume totals 571,293 m^3.

Seepage during reservoir impoundment is a common issue observed in many dams worldwide. Seepage in fractured or unconsolidated terrains can escalate to erosion, which ultimately leads to the formation of concentrated leakage pathways. This can jeopardize the stability of a dam and result in unforeseen dam failure. Therefore, the hydraulic and mechanical characteristics of the rock foundation are critical parameters in dam design [1]. Several methods have been developed to detect dam seepage. In addition to geophysical surveys such as ground-penetrating radar (GPR), self-potential (SP), and various types of logging (such as gamma-gamma, neutron-neutron, and caliper logging), permeability and pressure water tests are commonly used methods. The decision to install a grout curtain primarily depends on the results of these tests [2-3].

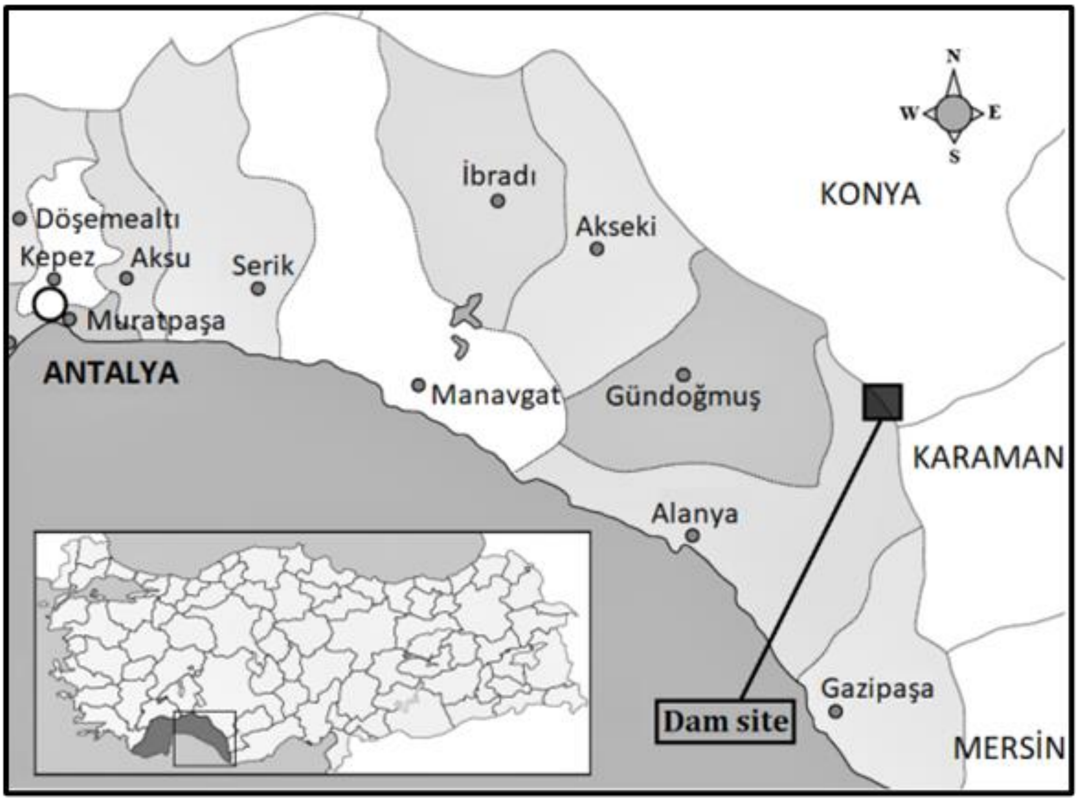

Figure 1. Location map of the Yalnızardıç Dam Site.

Grouting is one of the most common methods of foundation reinforcement, defined simply as the filling of fractures and gaps in the base rock with cement slurry, resulting in a relatively impermeable rock mass, greater strength, and reduced deformability. The success of this method depends on the overall properties of the ground, which include irregularities, apertures, and the space volumes of the fractures. These factors directly influence the grout mixture and quantity needed for effective application. Grouting is used in dam construction to reinforce the foundation of the dam. This is achieved by making the ground impermeable, preventing seepage through the foundation, reducing hydrostatic pressure on the downstream side, and obstructing the washout and erosion of fine-filling materials. Despite being designed to prevent leakage, dams may still experience seepage. In such cases, preventing piping is crucial, and this is achieved by grouting with appropriate materials based on the results of the Lugeon test. Grouting often constitutes a significant portion of the dam budget [1, 4-6].

Grouting in dam engineering has been extensively studied to enhance the strength and durability of weak soils while reducing permeability. Kocbay and Kilic [7] investigated the engineering geological properties of rock masses in the Obruk Dam region of Turkey. The study focused on various factors such as discontinuities, degree of weathering, strength, and hydraulic conductivities, to identify potential problems and necessary precautions for construction. However, no recommendations were provided regarding impermeability. Agan [8] suggested the use of grout at the Mezra Dam site in Turkey. However, the focus of the study was primarily on presenting the findings of site investigations, rock mechanics, and geological assessments. Gürocak and Alemdağ [9] assessed the depth of grout and conducted seepage analyses using the finite element technique at the Atasu Dam site in Türkiye, based on the values obtained from Lugeon tests.

Kociánová et al. [10] focused on novel techniques for remediation grouting and examined the composition of grout mixtures. Lin et al. [5] developed a new grouting model for a super high arch dam, while Chhun et al. [11] investigated the impact of a newly developed cement grout on the strength of silty sand through a laboratory study.

The seepage of the dam foundation and body following impoundment, as well as the measures taken to prevent it, were examined in case studies by Turkmen [12], Chun et al. [13], and Ozcelik and Tuzlu [14].

Alkaya and Yeşil [15] investigated the grouting procedure of the Cindere Dam in Türkiye, while Ozcelik [16] examined the Deriner Dam in Türkiye.

Numerous studies have been conducted on specific aspects related to dams, such as the grouting procedures [15-16], case studies about seepage following dam impoundment [12-14], grout techniques and mixtures [5, 10-11], and geological properties of rock masses [7-9], including discontinuities, degree of weathering, strength, and hydraulic conductivities.

This study presents an analysis of the geotechnical properties of rock masses, including permeability and rock quality designation, at the Yalnızardıc Dam site in Turkey after grouting application in the foundation. The study provides a detailed description of the grouting application process based on the proposed method. The study uniquely assesses the effectiveness of the grouting application through a regional comparison of permeability before and after remediation, utilizing check boreholes.

2. Geological Characteristics of the Dam Site

The dam site is characterized by two primary geological structures dating back to the Triassic, Jurassic, and Cretaceous periods. The Derebucak Formation, depicted in Figure 2, is comprised of bituminous schist, limestones, carbonate cement conglomerate, sandstone, claystone, and limestone. This formation is composed of alternating thick and thin layers of sedimentary rocks, with a thick claypan layer on the surface in the upper zones. Additionally, conglomerates consisting of limestone, sandstone, and other materials of varying sizes can be found in this formation. The formation is situated to the north of the dam axis, and almost the entire dam lake area lies atop it. The Çamlık Formation, on the other hand, is composed of medium and thick-bedded Jura-Cretaceous dolomitic limestones and limestones. Petrographic analyses conducted on samples collected from the dam axis identified dolomitic limestone. The limestone member of this formation is located on the dolomite limestone on the right and left slopes of the Gevne valley downstream of the dam site.

In the dam axis area, the bedrock on the right abutment has undergone significant alteration, particularly in the surface and fault zones. Laboratory analyses conducted on alteration materials obtained from drill cores revealed that the soil type was classified as CL, SM, and SC based on the Unified Soil Classification System. The Atterberg Limits of the clay component of these samples were assessed, and the swelling was evaluated through laboratory analyses. Specifically, the plasticity of the sample collected from the 11-12 m alteration zone of the SK-6 well was found to be 27% (indicating high swelling), as illustrated in Figure 3.

Based on the Turkish Earthquake Zoning Map provided by the Turkish General Directorate of Disaster Affairs, the Yalnızardıç dam site is located within the fourth-degree earthquake zone.

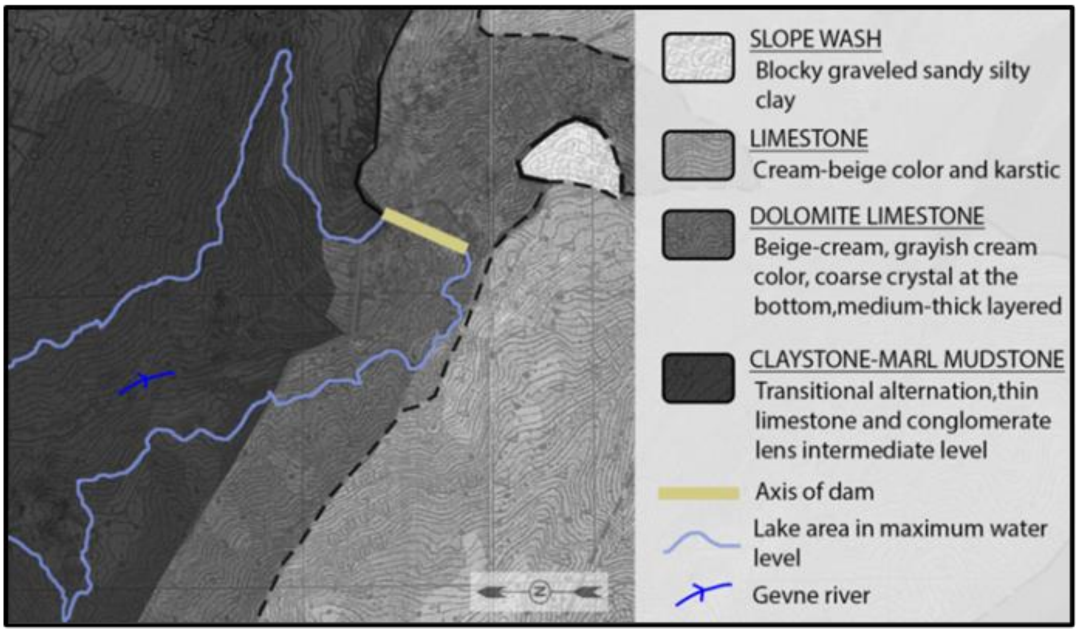

Figure 2. Geological map of the Yalnızardıç Dam.

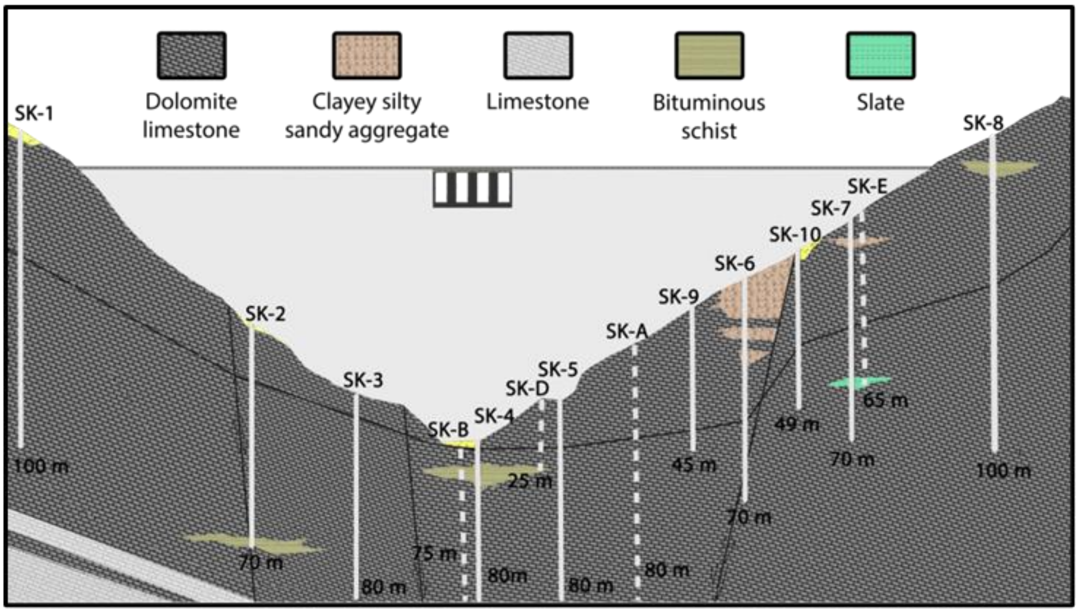

Figure 3. Geological profile of the dam foundation.

3. Engineering Geotechnical Investigations

Geotechnical properties of the dam area were examined through boreholes drilled in the river area and along the dam axis, as depicted in Figure 4. This investigation primarily focused on groundwater levels, Lugeon permeability parameters (Lu) of the zones, and Rock Quality Designation (RQD).

3.1 Drillings

To identify key ground properties such as groundwater levels, permeability, and rock quality, boreholes were drilled before the dam's construction. The grouting method was then prepared by these factors. The drilling process occurred in several locations, including the thalweg, riverbed, left and right abutments, and energy tunnel. The General Directorate of the State Hydraulic Works in Türkiye (DSI) carried out the drilling process, as shown in Figure 3 and Figure 4. During the drilling process, groundwater was observed in cracks, faults, and alteration zones of both the alluvial cover and bedrock. This groundwater flowed from the slopes towards the stream. Table 1 displays the results of Lugeon permeability, rock quality designation (RQD) and triaxial compression test values for the dam axis, including their mean values.

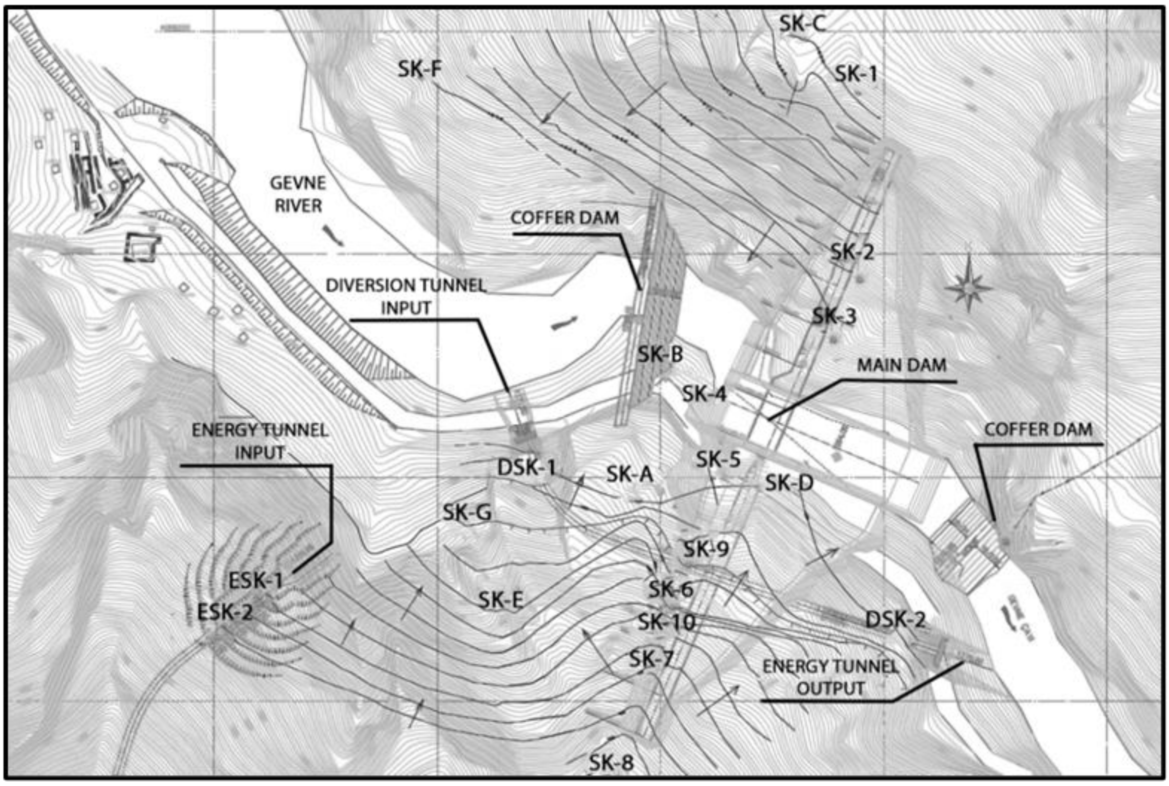

Figure 4. Location plan of the drillings

Table 1. Geotechnical parameters of the boreholes.

Location	Borehole Number	Depth (m)	Permeability (Lugeon)			RQD (%)		
			Min	Max	Ave	Min	Max	Ave
Left Abutment	SK-1	100	0,70	48,40	4,00	11	96	46
	SK-2	70	0,10	13,80	2,10	0.0	88	49
	SK-3	80	0,20	7,90	2,00	0.0	96	56
Thalweg	SK-4	80	0,30	25,10	4,40	4.0	88	50
Right Abutment	SK-5	80	0,60	60,60	5,50	29	95	75
	SK-6	70	0,10	13,80	3,20	0.0	91	45
	SK-7	70	0,50	10,30	2,00	0.0	90	55
	SK-8	100	0,00	14,20	2,70	12	98	80
	SK-9	45	0,30	8,90	1,30	0.0	93	50
	SK-10	49	1,00	12,10	4,10	0.0	60	27

The bedrock in the dam axis area was exposed to severe alteration, leading to the formation of alteration clay zones. Based on the Atterberg limits of samples taken from these clay zones, it was determined that the clay materials, particularly in samples taken from the SK-6 borehole area on the right bank, exhibited a "high swelling" characteristic.

3.2 Permeability and rock quality designation (RQD)

The permeability of the base rock at the dam foundation was determined using pressured water-pumping tests (WPTs). In total, 247 WPTs were performed in the thalweg, left and right abutments. The Lugeon values (Table 1) were used to explain the permeability. The results of the 247 WPTs showed that 37% of the base rock was impermeable, 45% was d-permeable, 16% was permeable, and 2% was highly permeable (Figure 5a).

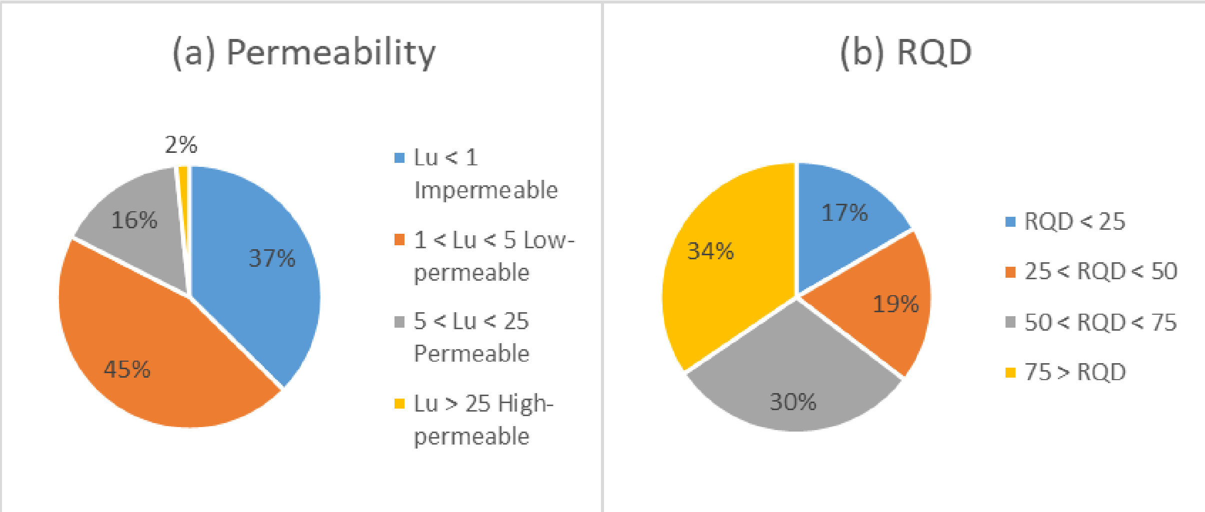

Figure 5. Results of the (a) WPTs and (b) the RQD for all drillings in the dam axis.

RQD is a value used to characterize the rock mass. It is defined as the total length of borehole stick samples over 10 cm identified as a percentage of the total core line length. RQD values range from 0 to 100 and have corresponding engineering quality categories. For example, an RQD value of 0-25 is considered very poor, while an RQD value of 90-100 is considered very good. Generally, low RQD values indicate highly fractured rock requiring grouting [17]. The RQD values for all boreholes in the dam axis are shown in Figure 5b. The results show that 35% of the samples had very poor to poor RQD values, 30% had medium values, and 35% had good values.

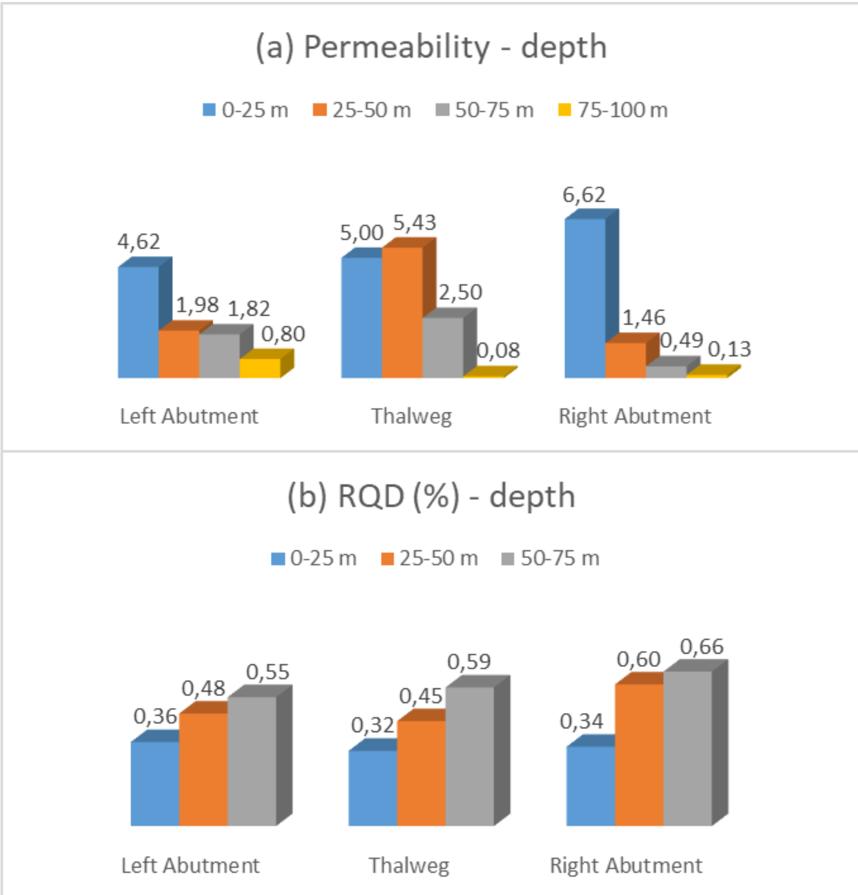

Figure 6. (a) WPTs and (b) RQD values by location in the dam axis.

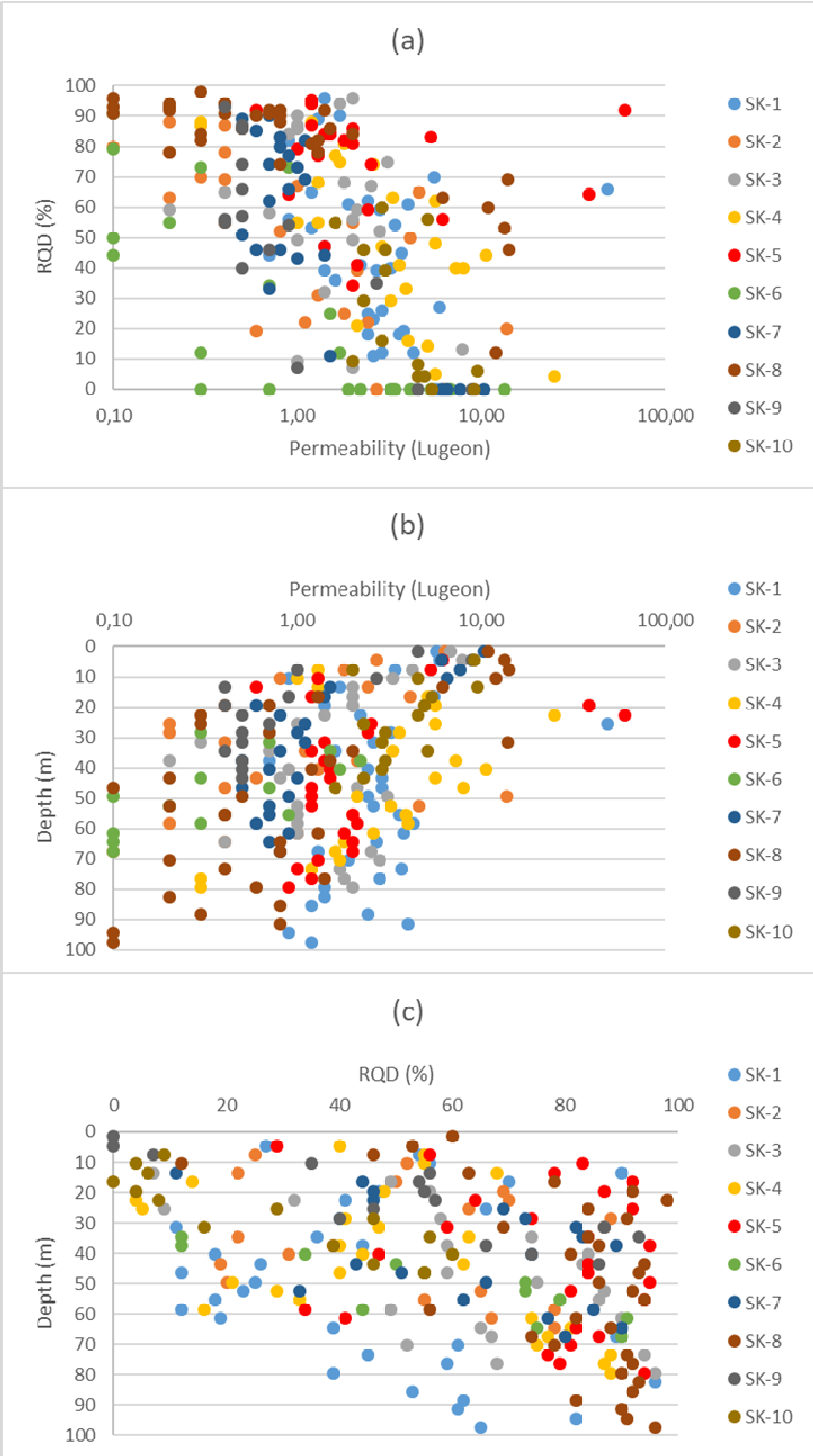

Figure 7. The correlations among (a) permeability and rock quality, (b) permeability and depth, and (c) rock quality and depth for rock units [23].

The WPTs results showed the presence of low-permeable and permeable zones at depths of 0-50 m. The Lu values of the rock mass went below 1, making it impermeable between depths of 50-100 m (Figure 6a). The RQD results showed poor values at depths of 0-25 m, with an increase in values as depth increased (Figure 6b). The occasional presence of permeable and high-permeable zones was observed at depths of 0-40 m (Figure 7b).

While many studies have reported that permeability generally decreases with depth, there are also exceptions to this trend [18-20]. Berhane and Walraevens [21] found that hydraulic conductivity tends to decrease with depth based on an analysis of borehole data. Interestingly, they also found no direct correlation between RQD and Lugeon values. However, in the case of the current study, it appears that permeability increases with poor RQD (Figure 7a), but still decreases with depth overall (Figure 6a). On the other hand, RQD tends to increase with depth for the rock units examined in this study (Figure 7b, 7c).

3.3 Rock quality classification

The bedrock was classified according to the RMR (Rock Mass Rating) system, based on the information obtained within the scope of this study, taking into account the RQD value, groundwater conditions, crack spacing, crack characteristics, and the uniaxial compressive strength that represents the in-situ rock conditions as a mass. The sum of the RMR scores and rock quality classes for the bedrock were presented in Table 2, categorized by region.

Table 2. RMR and Rock quality classification.

Location	RMR Score					Rock quality classification
	uniaxial compression	RQD	Crack spacing	groundwater	Total RMR score	
Left abutment	12	8	8	4	32	IV- weak rock
Thalweg	12	8	8	4	32	IV- weak rock
Right abutment	12	13	18	7	50	III-medium rock

3.4 Grouting studies

The correlation between depth and permeability of the base rock at the dam axis is illustrated in Figure 6a. Generally, the conductivity of the units at depths of 0-50 meters is low, with permeability ranging from low to moderate levels. The shallow units of the base rock have the potential to cause leakage following the construction of the dam. Therefore, measures such as enhancer curtains and blanket grouts have been proposed to mitigate permeability beneath the left and right abutments, as well as along the thalweg.

Consolidation (blanket) grout is usually designed shallow and its aims to reinforcing faults by reduce permeability and increase rock strength [8]. In this study, blanket grout holes were built as 5 m deep, and with square pattern, and with 2 m intervals (Figure 8b). In the SK-6 borehole located at right abutment of the dam axis, alteration zones (0-18 m) were removed and replaced with backfill concrete. The multi-cracked bedrock between 18-27.5 meters was strengthened by the blanket grout.

Curtain grouts are designed to obstruct seepage and serve as a barrier beneath the dam axis prior to the construction of the dam body. They can also be used for repair purposes following construction. This process involves drilling vertical holes at intervals that intersect to form a curtain, which is then filled with pressurized grout [8]. Thus, the curtain grout holes were drilled to a depth of 30 m (front) and 70 m (back), using a double line pattern with 3-meter intervals (as shown in Figure 8a). As the existence of bituminous schists in the bedrock could lead to increased seepage when washed with pressurized water, the grout curtains were extended to deeper levels to prevent this issue. In areas of high permeability in the abutments, groundwater flows from the slopes towards the streams. To address these areas, grouting galleries were constructed, and the curtain grouts were extended 37 m in the left abutment and 45 m in the right abutment towards the slopes. Grout boreholes were drilled using the shortened distance method and the grout area was divided into three-meter sections. The boreholes were grouted in the following sequence: A, B, C, and D.

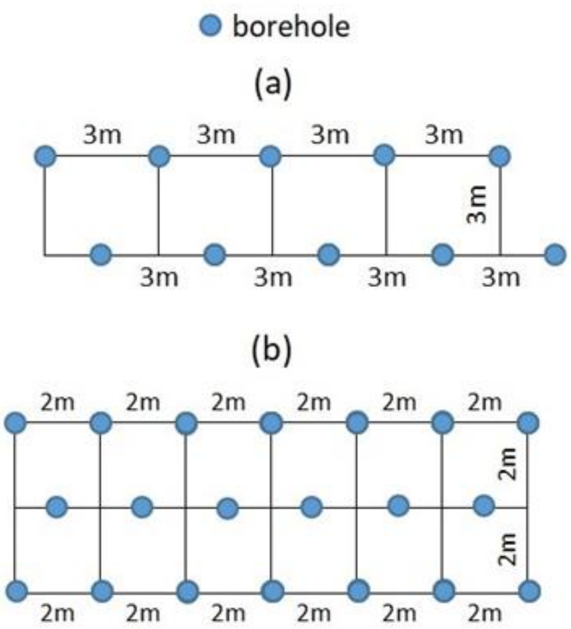

Figure 8. Details of (a) curtain grouts, (b) blanket grouts.

Moreover, inclined grouts were constructed to connect the curtain grouts that were vertically drilled. These inclined grouts were designed to be 3 meters apart and 15 meters deep at a 15-degree angle. Inclined radiating grouts were also built on both the right and left abutments' galleries, extending from the curtains. These grouts were drilled at specific angles and to a depth of 5 meters.

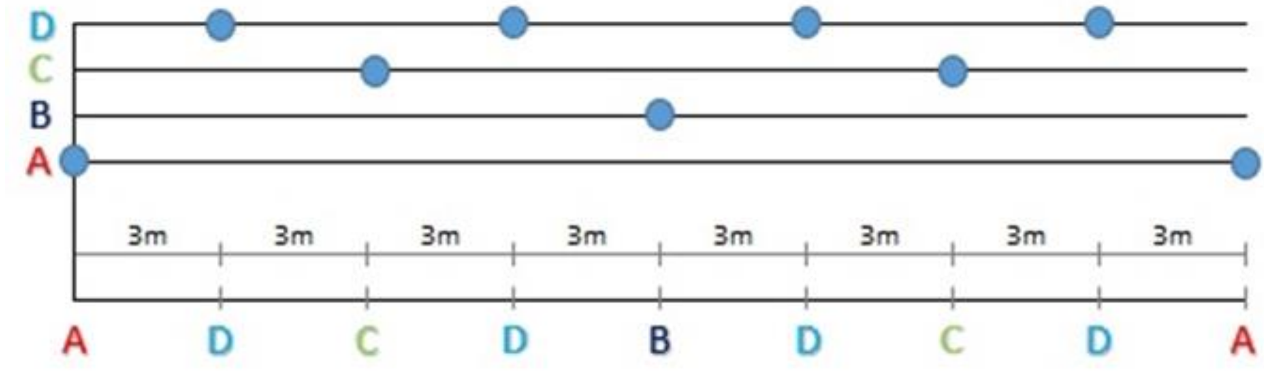

Figure 9. The drilling plan executed using the shortened distance method.

3.5 Performance evaluation of control boreholes

To assess the effectiveness of the grouting procedure after the completion of the curtain grouting structure, check boreholes were drilled to intersect multiple boreholes at various angles, and WPTs were performed. The depths of the check boreholes, which were drilled during the grouting works, varied between 75 m and 95 m, depending on the conditions of the area (as illustrated in Figure 10). Table 3 displays the permeability values and their mean values of the control boreholes in the dam axis. The results, as shown in Figure 11a, 11b, 11c, demonstrate a decrease in permeability in the thalweg, left, and right abutments, indicating the effectiveness of the grouting process. In general, the Lugeon test results in the thalweg exhibited higher values than those of the right and left abutments.

The results demonstrate a reduction in permeability in the thalweg, left abutment, and right abutment, indicating the effectiveness of the grouting process (refer to Figure 11a, 11b, and 11c). Specifically, the Lugeon test results show higher permeability values in the thalweg compared to those of the right and left abutments.

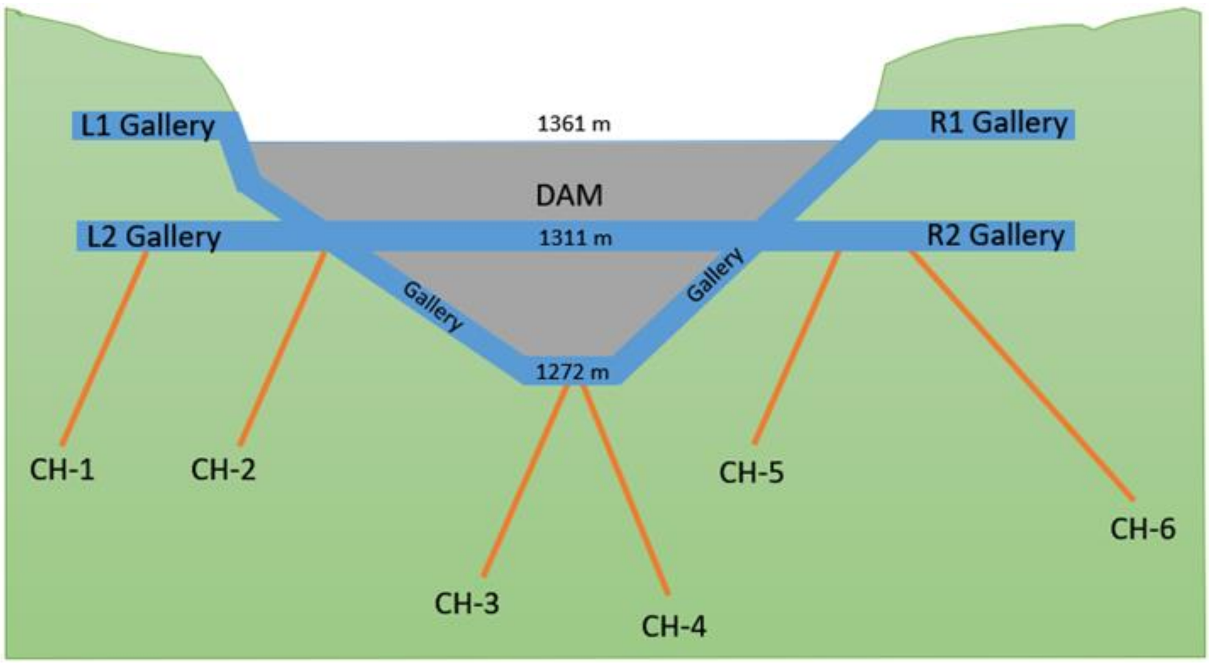

Figure 10. Location of control borehole.

Table 3. Geotechnical parameters of the check boreholes.

Location	Borehole Number	Depth (m)	Angle of Gradient (°)	Permeability (Lugeon) Min	Max	Ave	Ave
Left Abutment	CH-1	90	31	0,10	1,60	0,60	0,70
	CH-2	90	28	0,10	4,00	0,90	
Thalweg	CH-3	75	42	0,10	3,20	1,40	1,90
	CH-4	75	29	0,10	13,20	2,40	
Right Abutment	CH-5	95	37	0,10	8,70	2,00	1,30
	CH-6	95	32	0,10	1,60	0,70	

Figure 11. Comparing permeability before and after grouting at the dam axis [23].

4. Conclusion

This study focuses on the geological characteristics and engineering geological conditions of the Yalnızardıç dam site, which is located in an area underlain by the Derebucak Formation. This formation comprises various rock types, including bituminous schist, limestones, carbonate cement conglomerates, sandstones, claystones, and limestone, all of which date back to the Triassic, Jurassic, and Cretaceous ages. Additionally, the site is situated in the Çamlık Formation, characterized by medium to thick-bedded Jura-Cretaceous dolomitic limestones and limestones.

Leakage and rock quality in the foundation are crucial design parameters for dam constructions. In particular, the construction of curtain and consolidation grouts can enable the creation of a stable and impermeable foundation structure. The geological investigation, drilling (including RQDs, borehole logs, etc.), and Lugeon tests have shown that it is necessary to treat the foundations. Based on the results of WPTs conducted at the 0-50m depth of the dam foundation, the bedrock was determined to have both low permeable and permeable characteristics. Additionally, occasional high-permeable zones were observed at depths of 0-40m, which indicates that excessive leakage through the rock foundations can be expected. The RQD analysis results indicate poor values at 0-25m depth, which increase linearly with depth. The relationship between depth and permeability for the base rocks of the dam area shows a reduction in permeability with increasing depth. Additionally, the RQD results indicate that there is an increase in permeability when RQD values are low.

During the grouting works, the alteration zones of the bedrock were removed and replaced with backfill concrete. Consolidation grouts were constructed at a depth of 5m in a square pattern, with 2m intervals throughout the dam foundation. Additionally, curtain grouts with two lines of grouting holes were built to a depth of 30m and 70m for the left abutment, thalweg, and right abutment.

The conclusions of this study are as follows:

- Prior to the grouting works, it was observed that 33%, 12%, 45%, and 37% of the sections at the left abutment, thalweg, right abutment, and total dam site, respectively, had LU values of less than 1, indicating nearly no flow records. Additionally, 58%, 54%, 36%, and 45% of the sections at the left abutment, thalweg, right abutment, and total dam site, respectively, had LU values ranging from 1-5, indicating low permeability. Finally, 8%, 31%, 18%, and 16% of the sections at the left abutment, thalweg, right abutment, and total dam site, respectively, had LU values greater than 5, indicating permeable and high permeable conditions.
- After the grouting works, it was observed that 84%, 32%, 64%, and 61% of the sections at the left abutment, thalweg, right abutment, and total dam site, respectively, had LU values less than 1. Additionally, 18%, 61%, 31%, and 35% of the sections at the left abutment, thalweg, right abutment, and total dam site, respectively, had LU values ranging from 1-5. Finally, 0%, 7%, 6%, and 4% of the sections at the left abutment, thalweg, right abutment, and total dam site, respectively, had LU values ranging from 5-25, and no values exceeding 25 LU were observed.
- After grouting, the mean LU values significantly decreased at all locations. Specifically, the mean LU values decreased from 2.80 to 0.70 at the left abutment, from 4.00 to 1.90 at the thalweg, from 4.00 to 1.30 at the right abutment, and from 3.20 to 1.30 at the total dam site.

The results indicate that the parameter values are within the advised limits by DSI [22]. Therefore, it can be concluded that the grouting process was appropriate and effective considering the geological structure.

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Author contributions

Ömür Çimen: Literature review, Writing-Original draft preparation, **Halil İbrahim Günaydın:** Analysis and Evaluation of results, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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